X63-12264

SOLAR COLLECTOR DEVELOPMENT

By

Atwood R. Heath, Jr. and Preston T. Maxwell

The variety of methods under development for conversion of thermal (solar) energy to electricity, have stimulated a broad parallel interest in the development of solar collectors. Such devices are required to concentrate the relatively low level solar energy (about 130 watts/sq. ft. at the earth's orbit in space) to a usable density (temperature) for the particular energy conversion method to be employed.

As with most things, whether technical, political, or spiritual, there are proponents of many alternative methods and materials for the fabrication of solar collectors, each of which may be shown to have advantages for particular applications. Thus, it appears worthwhile to list the principal factors which must be weighed or considered. These factors may be briefly enumerated, not necessarily in order of importance, as follows:

(1) Operating temperature of the energy conversion device or system.

(2) Efficiency.

(3) Weight per unit projected area.

(4) Specific power – thermal energy per unit weight at a specific temperature.

(5) Prelaunch storage volume and deployment method.

Many other factors such as structural integrity and stiffness, potential optical degradation due to thermal gradients and space environment effects, scalability to higher power levels, requirements for masters, and magnetic properties, must also be considered.

Within the foregoing framework, an assessment of the state-of-the-art of solar collectors (concentrators) follows.

Figure 1 shows sketches of six different concepts of lightweight solar energy collectors[1]. These six concepts are not the only ones being considered, but are those concepts that have been developed to a point where quantitative data on their capabilities exist. Examples of the six types are listed in the table with some of their pertinent characteristics. All of the collectors are paraboloids with the exception of the Fresnel which is essentially a flat collector made up of annuli of paraboloids having a common focus. A description of each of the types with some details of the materials and methods of fabrication follows.

The Fresnel collector[2] is shown in figure 1 and the folding arrangement which consists of four hinged panels is indicated. The Fresnel surface is made by electroforming nickel on a steel master that has been machined and polished. The Fresnel electroform is then bonded to an electroformed stiffening structure.

Shown next is one form of an inflatable type collector[2]. The collector is pressurized and is formed of an aluminized Mylar paraboloid and a clear Mylar front cover. An inflated torus also made of Mylar is attached to the outside of the collector at the junction of the reflecting surface and the front cover.

A sketch of the inflatable-rigidized collector(3, 4) is shown next. Basically, this collector is an aluminized plastic paraboloid which would be rigidized in space by the application of a foamed plastic to the back of the collector.

The next sketch shows a one-piece collector(5, 6). One method of fabricating this type collector consists of electroforming a thin dish of nickel on an appropriate master. The dish is then stiffened by the addition of an electroformed torus to the periphery of the dish. Another method of one-piece collector construction utilizes a honeycomb sandwich that consists of a cast epoxy plastic-reflecting surface bonded to an aluminum honeycomb which is in turn backed up by a plastic Fiberglas panel. The reflective face can be cast on any suitable convex master. Several collectors have been made by this method of construction(7). Several other one-piece collectors have been constructed by methods such as spin casting of plastic(8), hydroforming of aluminum(9), and stretch-forming of aluminum, but complete quantitative data on the capabilities of these collectors are not currently available.

Next is shown a sketch of a petal collector. There are several variations of this type, but in all cases, the collector consists of a hub with attached petals which fold up to form a compact package for launching. A deploying system consisting of springs, cables, or mechanical linkages is used to open these devices. Several collectors of this type have been built, and different methods have been used in the construction of the petals for each. One collector[2] had petals of electroformed nickel, monocoque construction. Two others[8, 10] had petals of honeycomb sandwich which consisted of an aluminum reflecting face, honeycomb, and back. Another[11] had petals formed of a thin aluminum face which was stiffened by a light aluminum lattice truss spot welded to the back.

The last sketch shows an umbrella type collector[12]. This collector consists of an aluminized Mylar covering stretched over metal ribs. This collector also had an operational pneumatic erecting mechanism.

An important characteristic of a collector is the ability to collect the solar radiation efficiently and to provide the desired degree of concentration of the radiation commensurate with the ability of the conversion system to use the heat. Figure 2 shows the efficiency as a function of concentration ratio for the six typical collectors. The efficiencies have been measured with cold calorimeters which minimize reradiation so that the values are essentially only a function of collector geometry and specular reflectivity. The concentration ratio is based on the ratio of the projected reflective area of the collector to the aperture area of a cavity heat absorber. If a spherical absorber is used, the latter area is the surface area of the sphere.

As a goal to be obtained, a theoretical curve for a paraboloidal collector with a reflectivity of 0.91 is shown. The value of 0.91 is the value of reflectivity which might be obtained from a highly polished surface with a coating of vacuum deposited aluminum exposed to the solar spectrum. The one-piece collector data closely approach the theoretical curve which indicates that the master was of good quality and the reproduction process was faithful.

Four collectors fall in roughly the same range of concentrating ability, but with rather widely varying efficiencies. This failure to approach the theoretical potential can be attributed to conceptual, material, or fabrication problems. The petal collector had honeycomb markoff on the reflective face as well as some problems with reflective surface finish. The inflatable-rigidized collector had a reflectivity of only 0.83 which is the value for aluminized Mylar plastic and an (orange peel" effect caused by the foam backing was apparent. These two collectors were designed for use with mechanical systems, however, and did not require high concentrating ability. The Fresnel collector, of course, has an inherent shadowing problem which amounts to about a 0.14 loss in efficiency. In addition some undetermined loss occurred which could be caused by difficulties in polishing the master. The low efficiencies of the inflatable collector were attributed to large transmission and reflectance losses from the front face as well as the reflecting face. The concentrating ability of the umbrella collector is very low because the reflecting surface gores between the metal ribs take a non-paraboloidal shape.

To find the temperature capability of a collector, the collector must be combined with an absorber that radiates at its operating temperature. For purposes of comparison, a cavity absorber is assumed with an absorptivity and emissivity of 1.00. The solar constant which affects the reradiation term is assumed to be 130 watts per square foot. Then the efficiency data of figure 2 are combined with the reradiation losses of the assumed absorber to obtain the combined efficiency as a function of temperature as shown in figure 3. If a thermionic conversion system with operating temperatures near 4,000° R is required, only the one-piece mirror is capable of efficient operation at the present time. All of the expandable collectors are relatively inefficient even at temperatures around 2,000° R.

One of the principal aims of the development to date has been to construct practical collectors at a minimum weight. The results of these efforts are shown in figure 4. Only the petal collector has been built in enough sizes so that the variation of unit weight with diameter can be determined. These unit weights are essentially constant at about 0.20 lb/ft^2 with variation in diameter with the exception of one model at about 1.0 lb/ft^2. This model was basically a ground test model and is therefore not representative of a flight article. Construction of the one-piece collectors has been restricted mostly to one diameter (5 feet) because of the availability of masters. The unit weights vary quite widely from 0.40 to 1.04 lbs/ft^2 with the collectors having the lower weights also having poorer geometry. An estimated weight curve is given for the inflatable-rigidized collector because the ground test model had a unit weight of 3.82 lbs/ft^2 which is not indicative of the weight of a model to be used in space. An estimated unit weight curve(12) is also shown for the umbrella collector. Good agreement is indicated with the 5-foot and 10-foot models. No variation in unit weight with collector diameter is available for the Fresnel and inflatable collectors.

The selection of a collector for a given power conversion system might well be based on the specific power, i.e., the ratio of power to unit weight. Figure 5 shows the values of specific power for the six typical collectors. The combined collector-absorber efficiencies of figure 3 were used with the unit weights of the various collectors and a solar constant of 130 watts/ft^2 to obtain the values shown. In the temperature range of 1500 to 3500° R the inflatable collector delivers the most power per pound due to its extremely low unit weight. On the other hand, the very efficient one-piece electroformed collector has a relatively low value of specific power due to its heavier unit weight. However, when comparing these two collectors at the same value of specific power, the inflatable would have an area many times that of the one-piece collectors for power systems of the same output. This last fact brings up another consideration which should be mentioned. Large area collectors of low efficiency may well be undesirable because of possible interference with communications or other essential space-craft missions. Thus the systems engineer may have no choice but to select the most efficient collector even at the expense of increased weight.

Each of the collectors developed to date, with the exception of the one-piece type, has a folding or stowing feature for compactness during launch. The packaged volumes of the various types are shown in figure 6.

The one-piece collectors have the highest volumes for a given diameter. Of course the limiting factor for one-piece models is generally the launch vehicle diameter and the packaged volume as determined could be relatively meaningless.

The petal collectors are the next highest in volume which runs to over 700 cubic feet for a 32.2-foot-diameter collector. Minor reductions in the volume of this type might be made; however, no radical reduction in volume is expected.

The umbrella type has a fairly low volume at least for the 10-foot model, and the Fresnel volume is very low for the 4-foot model. A curve of the estimated volume of the inflatable-rigidized collector is given as an indication of what can be expected for this collector.

In considering objectives for continued development of solar collectors in the near future, certain assumptions must be made. First, it appears that future solar collector development efforts for thermal electric application should emphasize the temperature range from about 1,000° R to about 4,000° R, because conversion efficiencies for systems operating below about 1,000° R may be expected to be relatively low. Thus, excessively large solar collector areas would be required, even though low temperatures may be attainable at relatively low collector weights. Second, it appears that near future planning for solar-electrical power systems should be based on an extension of power levels to about 25 kw, thus requiring collectors in the 50 to 100 ft. diameter size range. Third, even as alternative thermal energy sources such as isotopes and nuclear reactors become operational as flight systems, it is expected that a continuing requirement will exist for solar-electric systems, due to considerations of cost, weight, and personnel safety in special applications.

To be more specific, it is expected that the rigid paraboloidal type concentrator will continue for some time to be the only practical approach to thermionic operating temperatures (about 4,000° R), with reasonable concentrator-absorber efficiencies. In concentrators of this type, a diameter of approximately 10 ft. is foreseeable with reasonable confidence. The extension of rigid concentrator sizes above 10-ft. in diameter should not be ruled out at this time, however, as future launch vehicles will permit rigid concentrators of 20-ft. diameter or larger should the requirement arise. Regarding fabrication methods and materials, the future is expected to see a continuing investigation of alternatives to the electroformed nickel concentrator which, while generally agreed to be at a relatively high state of development, has certain limitations; such as high weight and undesirable magnetic properties. For thermionic systems supplying relatively large amounts of power, it is expected that the trend will be to modular systems (multiple concentrators) as shown in an artist's concept in figure 7.

For solar dynamic systems (operating temperature about 1800° R), a central energy conversion system and a single concentrator would be considerably more advantageous than the modular approach envisioned above for high power thermionic systems. Thus, as the power level increases, a comparable increase in solar concentrator size will be necessary. Up to about 50-ft. in diameter, the petal type, the Fresnel type, or the inflatable-rigidized type appear potentially suitable. While the petal type, in this size range, may be somewhat closer to full scale ground tests, (the 32-ft. SUNFLOWER concentrator(13)) it must be emphasized that a clear-cut choice of deployable concentrators below about 50 ft. is not possible at this time.

Above 50 ft. in diameter, it appears that the prelaunch stowage problems, and structural stresses during launch and in ground handling, will necessitate going to an inflatable-rigidized concentrator. Further, while it must be recognized that many uncertainties are associated with the technology for rigidizing a large inflatable, optically accurate, structure in space, the potential usefulness and need for this capability will dictate a continuation of the current development effort.

Finally it is generally agreed that the technology for solar concentrators does not appear to be the pacing factor in the development of solar-thermal-electric power systems. Nonetheless, since other components of the system may be more readily scalable to large sizes, than are the solar concentrators, we cannot be assured that this situation will persist. Thus, an energetic continuation of the research and development effort to extend the technology for solar concentrators is essential, the level of effort and areas of emphasis being largely influenced by trends and developments in the related energy conversion methods and devices.

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TABLE I

EXAMPLES OF FABRICATED SOLAR COLLECTORS

Type	Method of construction	Material	Rim angle, deg	Diameter, ft.	Unit weight, lb/ft^2	Reference
Fresnel	Electroformed	Nickel	40.00	4.00	0.46	2
Inflatable	Stretch formed	Mylar	53.13	4.27	[b]0.08	2
Inflatable-rigidized	- - - - - - - - -	Mylar-foam	60.00	10.00	3.82	3, 4
One piece	Electroformed	Nickel	61.50	5.50	0.96	5
Petal	Stretch formed	Aluminum honeycomb	52.00	32.20	[a]0.18	8
Umbrella	60 Al. ribs	Mylar	90.00	10.00	[c]0.11	12

[a]Petals only
[b]Mylar only
[c]Ribs and Mylar only

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Captions

Figure 1. – Types of Solar Collectors.

Figure 2. – Collector Efficiency.

Figure 3. – Combined Collector-Absorber Efficiency.

Figure 4. – Collector Unit Weight.

Figure 5. – Collector Specific Power.

Figure 6. – Collector Packaged Volume.

Figure 7. – Example of Modular Collector Concept.

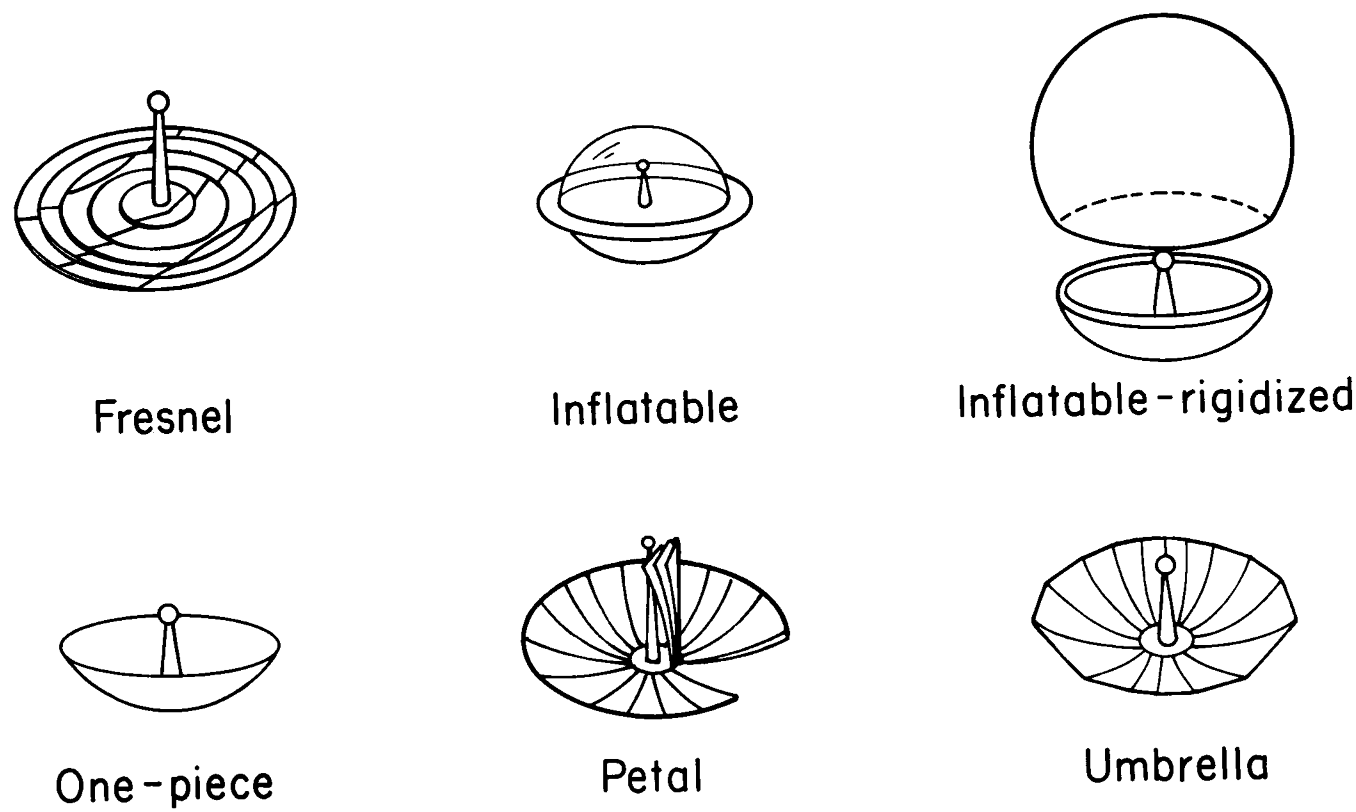
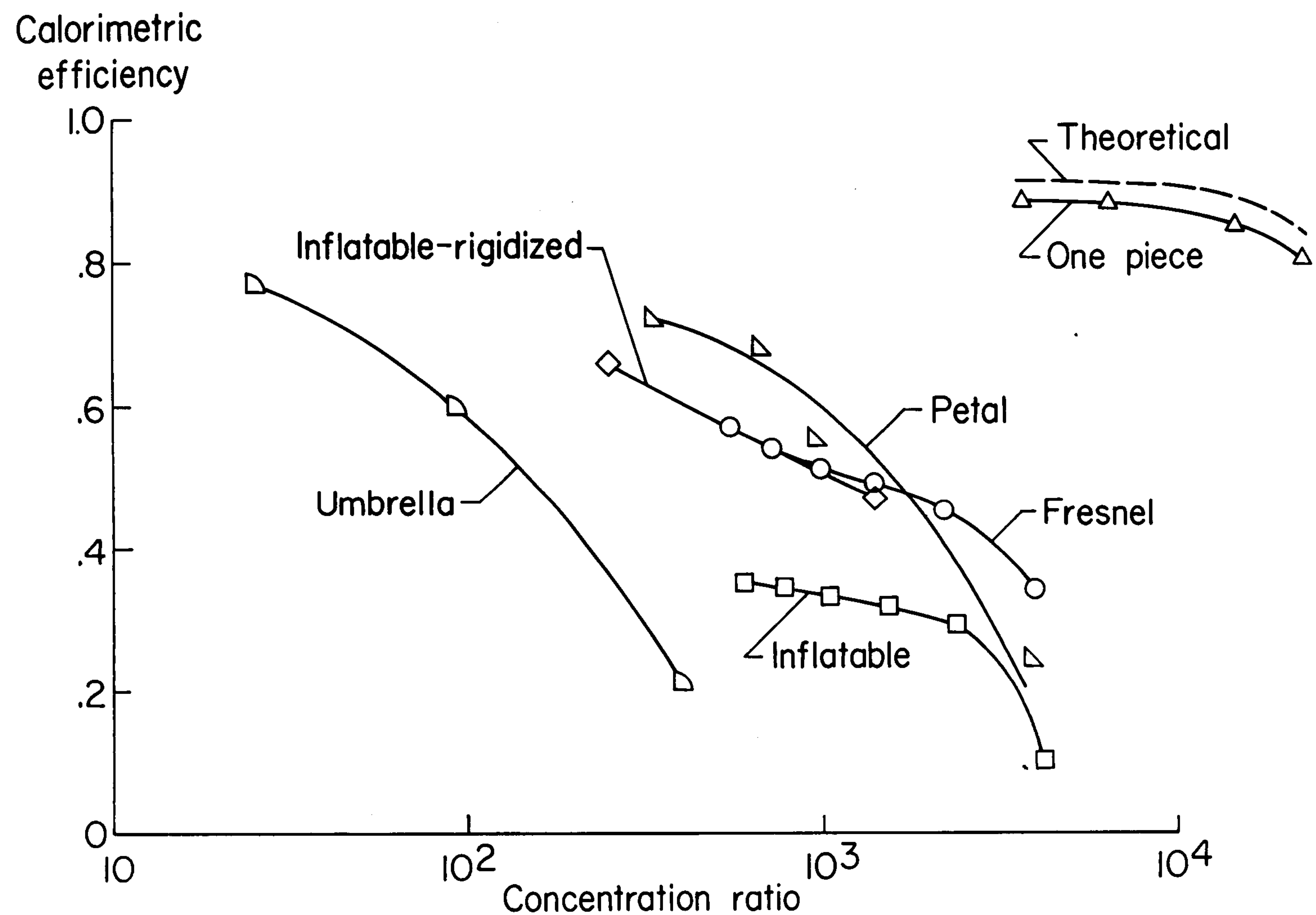
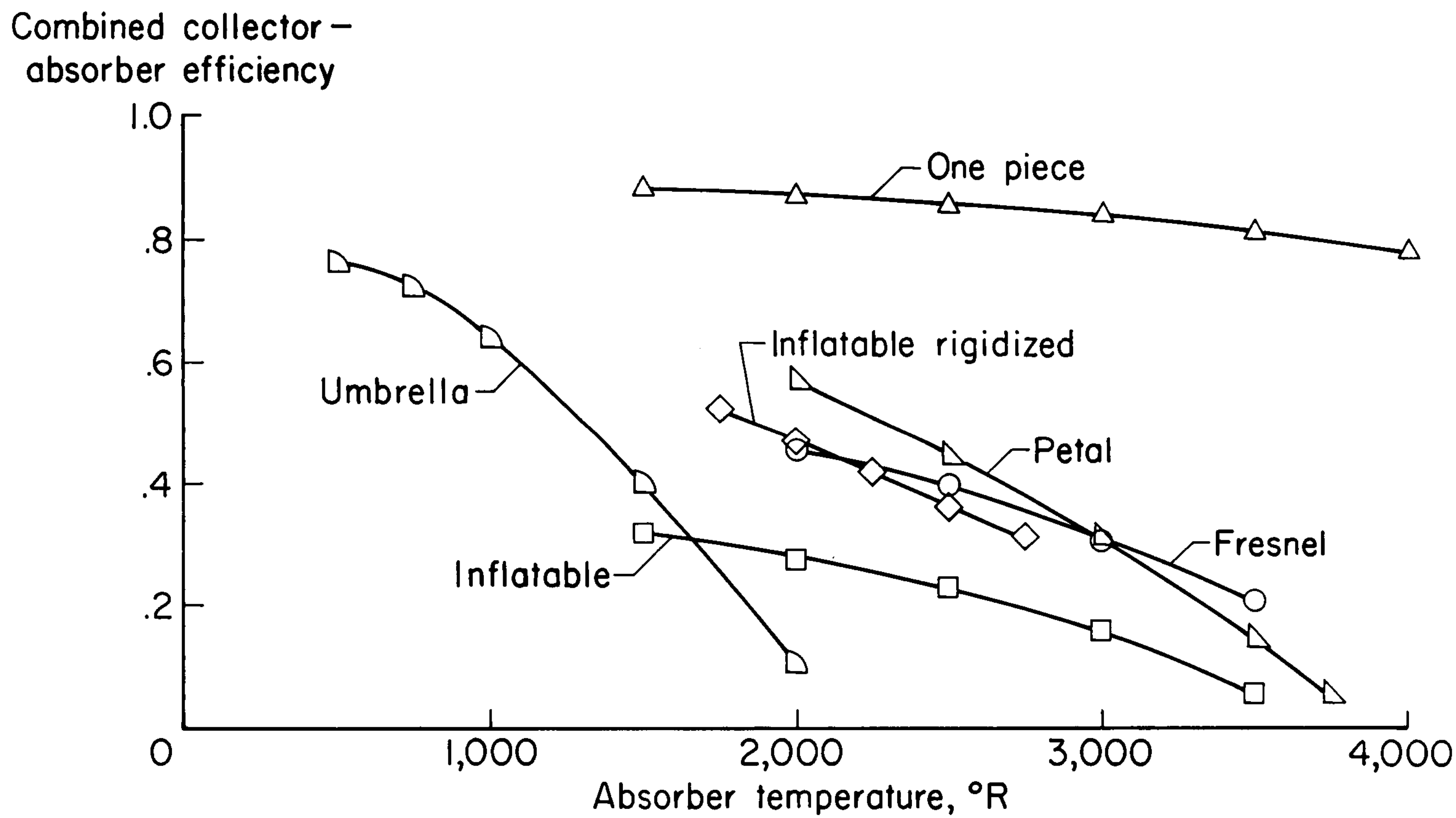

Fresnel
Inflatable
Inflatable-rigidized
One-piece
Petal
Umbrella

Fig. 1



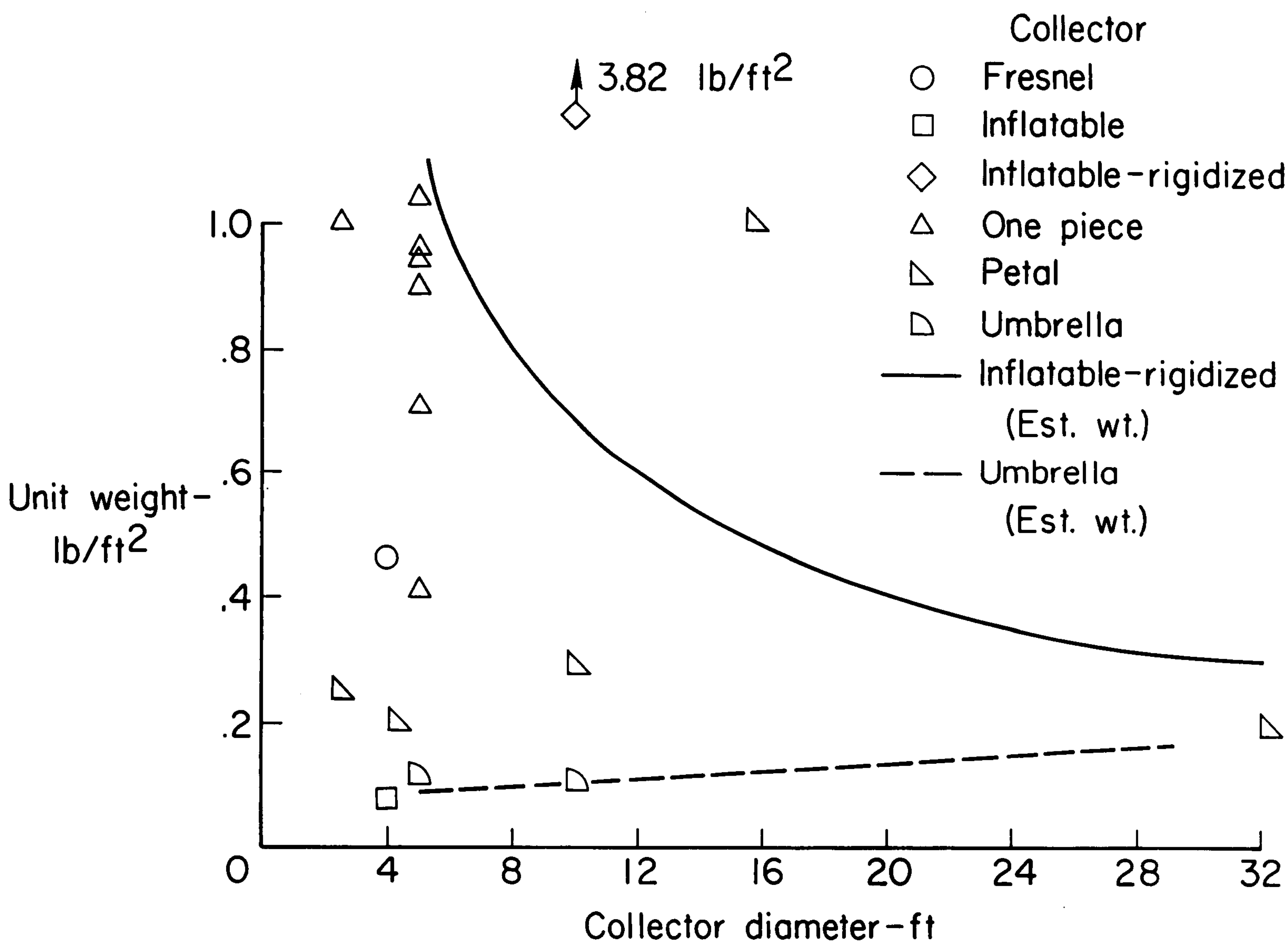
Calorimetric efficiency
1.0
.8
.6
.4
.2
0
10
10^2
10^3
10^4
Concentration ratio
Theoretical
One piece
Inflatable-rigidized
Petal
Umbrella
Fresnel
Inflatable

Fig. 2



Combined collector –
absorber efficiency
1.0
.8
.6
.4
.2
0
1,000
2,000
3,000
4,000
Absorber temperature, °R
One piece
Umbrella
Inflatable rigidized
Petal
Fresnel
Inflatable

Fig. 3



Collector
Fresnel
Inflatable
Inflatable-rigidized
One piece
Petal
Umbrella
Inflatable-rigidized
(Est. wt.)
Umbrella
(Est. wt.)
3.82 lb/ft2
Unit weight-
lb/ft2
1.0
.8
.6
.4
.2
0
4
8
12
16
20
24
28
32
Collector diameter-ft

Fig. 4

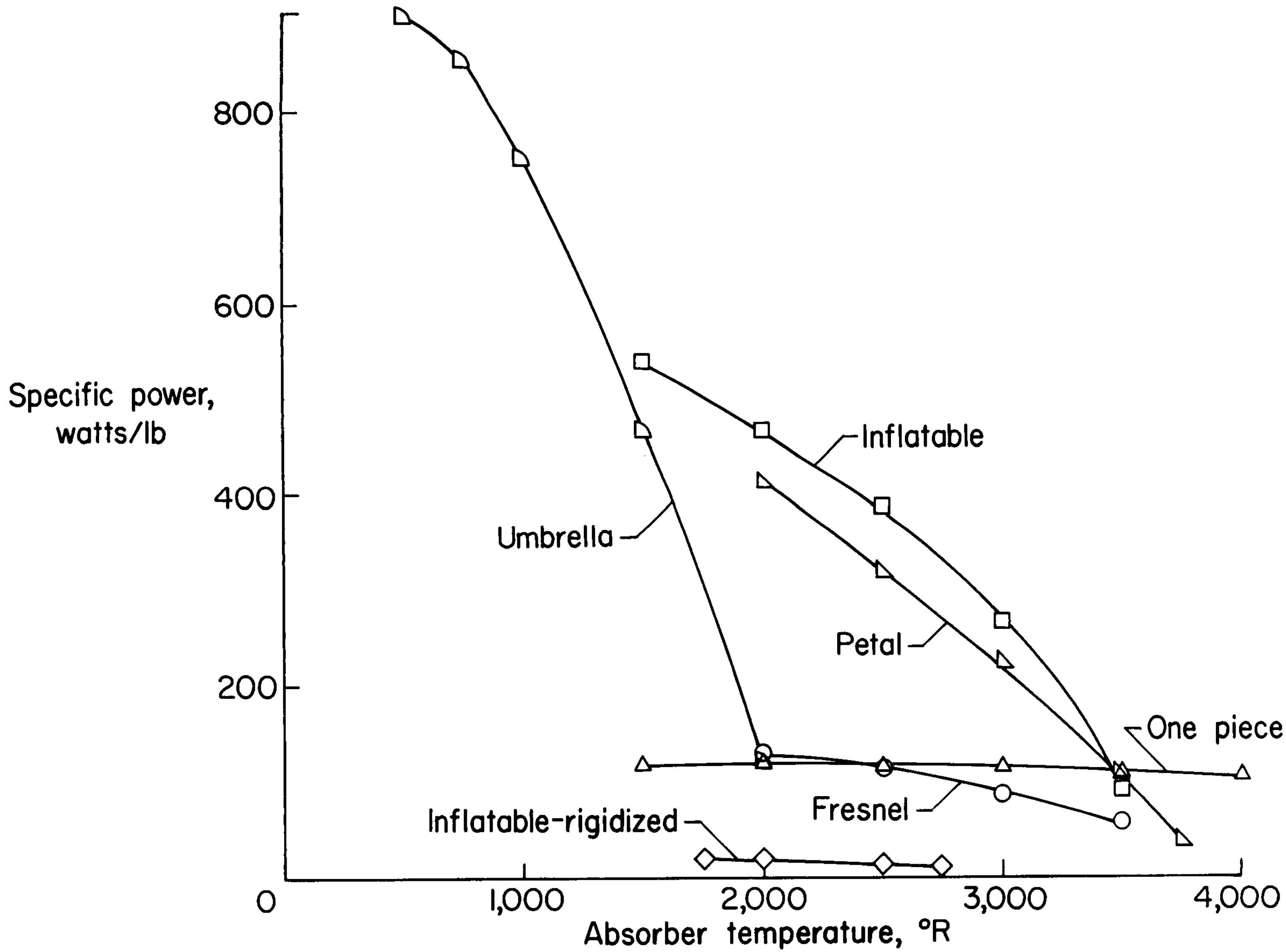
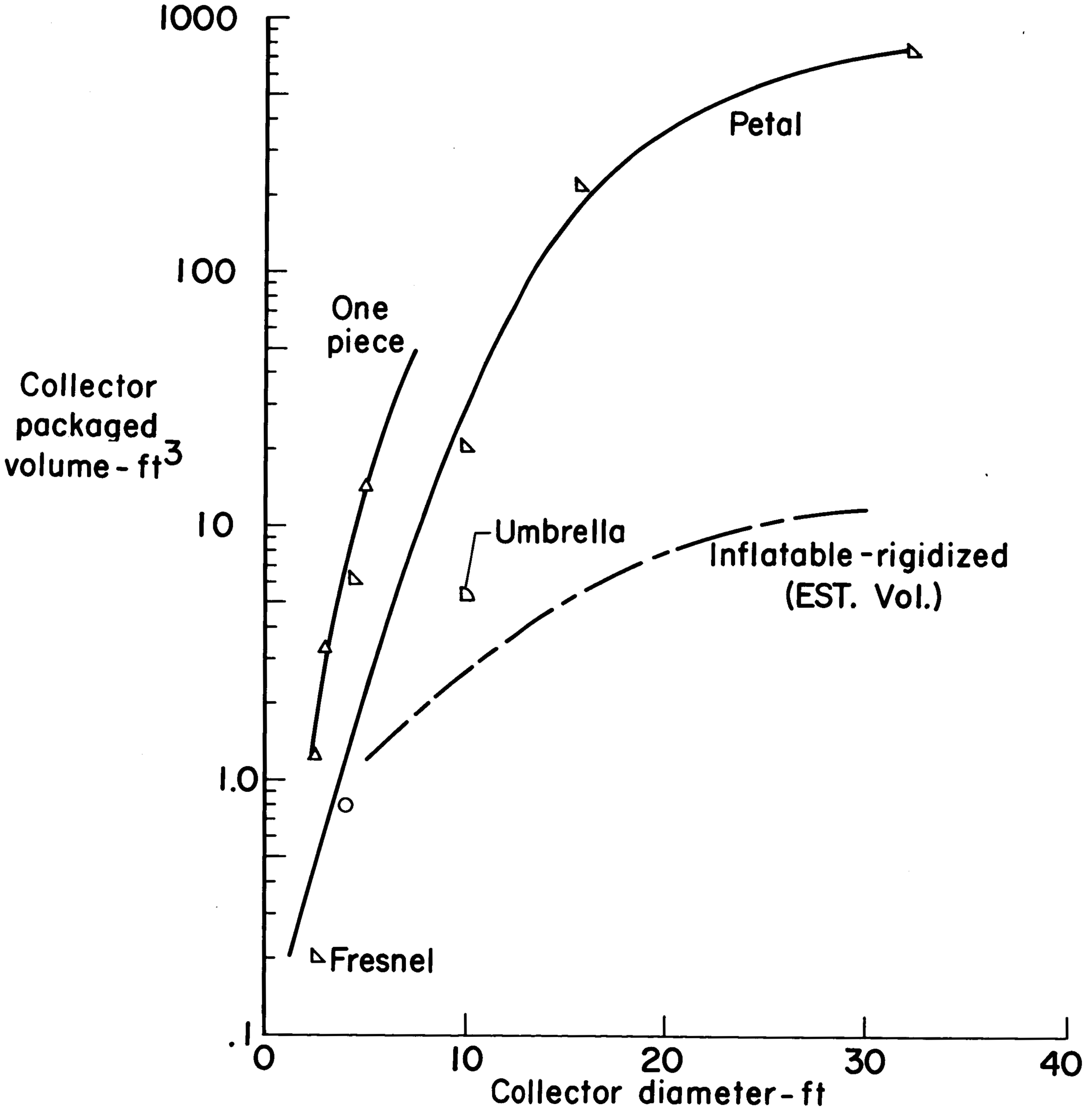

Specific power, watts/lb
800
600
400
200
0
1,000
2,000
3,000
4,000
Absorber temperature, °R
Inflatable
Umbrella
Petal
One piece
Fresnel
Inflatable-rigidized

Fig. 5



1000
100
10
1.0
.1
0
10
20
30
40
Collector packaged volume - ft3
Collector diameter - ft
Petal
One piece
Umbrella
Inflatable - rigidized
(EST. Vol.)
Fresnel

Fig. 6

NASA
L-63-1478

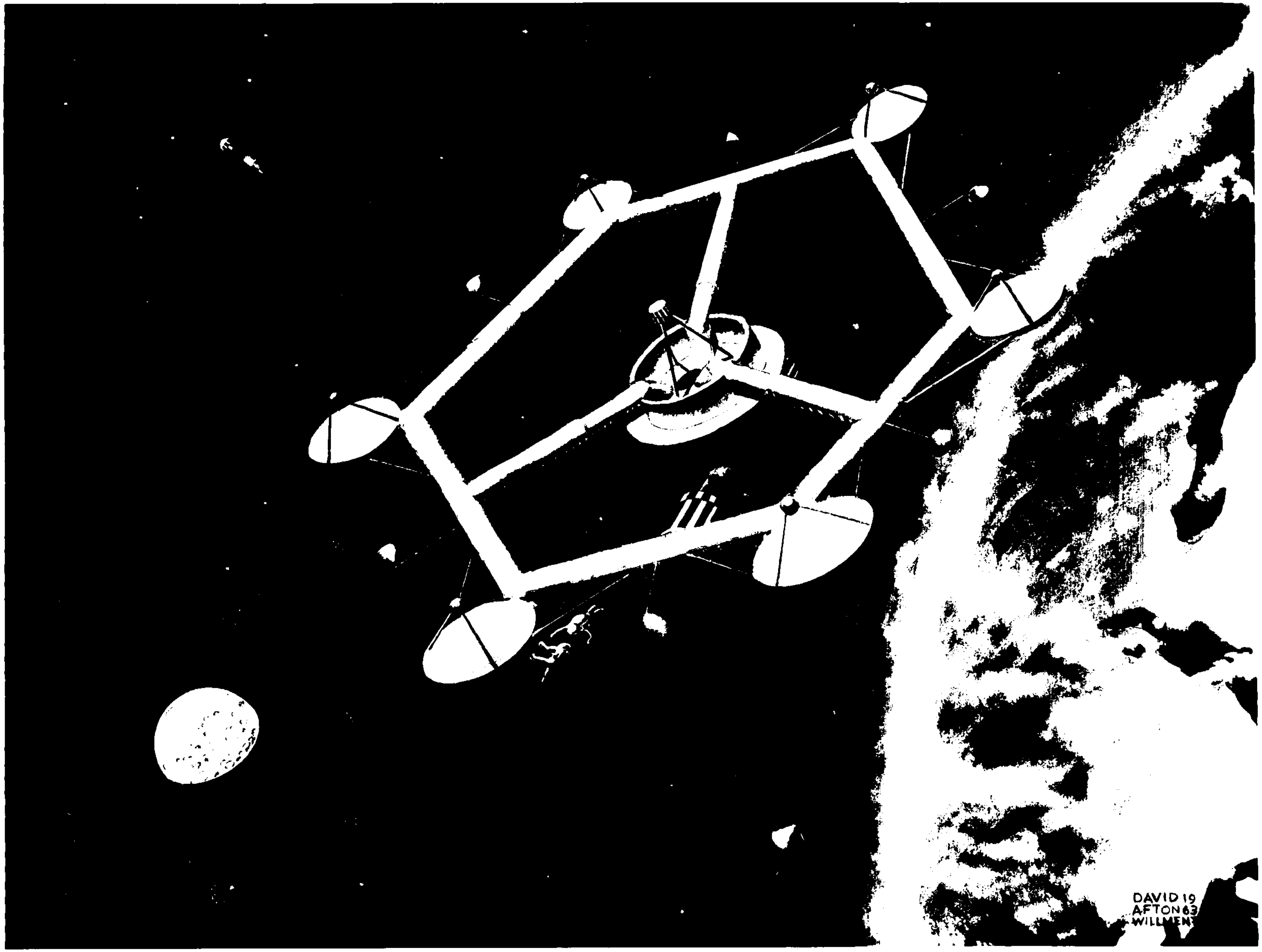


Fig. 7